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Reduction in nitrogen oxides emissions by MILD combustion of dried sludge

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ABSTRACT

Demands for the thermal treatment of sewage sludge are increasing due to the regulation of its ocean disposal and the desire to recover its potential energy. Because of the high nitrogen content in sewage sludge, one of the concerns about its combustion is a potential increase in NO_x emissions. Although a number of studies have been conducted to reduce NO_x emissions by combustion modifications, very few studies have addressed the combustion of dried sludge. In this study, a combustion technique called moderate or intense low oxygen dilution (MILD) was applied to the combustion of dried sludge with the goal of reducing NO_x emissions. MILD combustion of dried sludge was tested using both our laboratory-scale vertical combustor with internal circulation and our horizontal cyclone combustor with external circulation. Tests were conducted to find suitable operating conditions and to demonstrate the stable MILD combustion of dried sludge. From these tests, fuel and air flow patterns were found to be an important factor in maintaining stable MILD combustion, and the horizontal cyclone combustor demonstrated excellent performance in the reduction of NO_x emissions by the MILD combustion of dried sludge.

1. Introduction

The combustion of gaseous, liquid and solid fuels is a major emission source of nitrogen oxides (NO_x) [1]. Combustion modification and flue gas treatment are two representative NO_x emission control categories: combustion modification techniques are used to control NO_x formation during the combustion of fuels, whereas flue gas treatment techniques are used to remove NO_x from flue gases after NO_x is formed during the combustion [2]. Selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR) are the most widely used flue gas treatment techniques. SCR has demonstrated high NO_x reduction efficiency using catalysts that selectively interact with NO_x [3,4]. With SCR, a reducing agent such as ammonia is injected near the exit of the economizer zone; on the other hand, with SNCR, the ammonia is injected within the boiler superheater and reheater regions. Although the operating cost of SNCR may be lower than that of SCR, SNCR's narrow applicable temperature range increases its operational difficulty [1]. In addition to the flue gas treatment techniques, other common combustion modification techniques include staged combustion, gas reburning and flue gas recirculation [5,6]. Flue gas recirculation can reduce NO_x emissions by smoothing the temperature field within the furnace and by decreasing the adiabatic flame temperature [5]. In literature, this type of combustion is often called flameless oxidation because no visible flame develops during the combustion. Other common names for this technique are MILD combustion or, if the air is preheated to a high temperature, high temperature air combustion [5,7]. The term used in this paper is moderate or intense low oxygen dilution (MILD) combustion.

The amount of sewage sludge produced from wastewater treatment is increasing [8], but the Ocean Dumping Act is regulating the disposal of sewage sludge in the ocean. Sewage sludge is difficult to recycle because it is contaminated with trace metals [9], which has led to the suggestion of the thermal treatment of sewage sludge to destroy its toxic constituents. In addition, dried sewage sludge has a comparable heat value to low rank coal; thus, its energy content may be recovered through combustion [10]. One of the major concerns that arise from the potential combustion of sewage sludge is high NO_x emissions because of the high nitrogen content of the sludge. The high levels of metal oxides in sewage sludge were also reported to contribute to the increase in NO_x emissions [11].

This study was therefore designed to reduce NO_x emissions during the combustion of sewage sludge by using MILD combustion. Although a number of studies have been conducted on MILD

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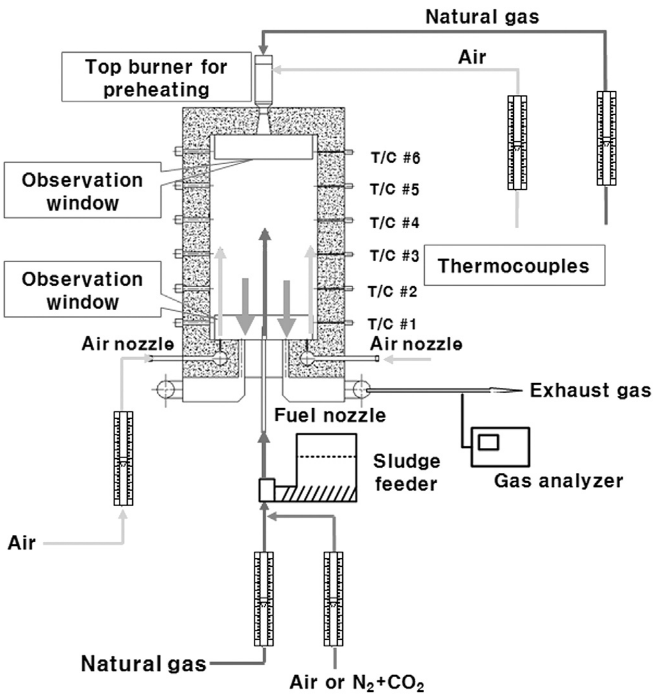


Fig. 1. Diagram of the vertical combustor with internal circulation.

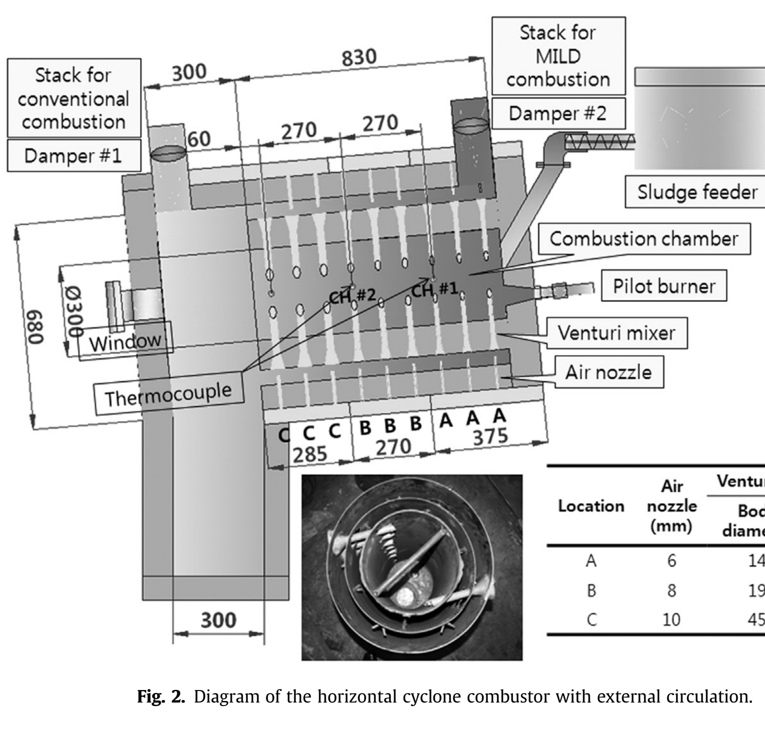
combustion of various fuels, most of those were conducted with gas or oil burners [5,7]. Very few studies are found on the use of MILD combustion to combust sludge.

Two laboratory-scale combustors were designed and constructed in this study: (1) a vertical combustor with internal circulation and (2) a horizontal cyclone combustor with external circulation. To determine the suitable nozzle diameters and flow rates of fuel and air in the vertical combustor, the flow pattern of fuel and air from a computational fluid dynamics (CFD) simulation and experimental data for the combustion of natural gas was analyzed. Preliminary combustion tests with dried sludge were conducted using both combustors to determine the suitable operating conditions. The performance of each combustor was evaluated with the temperatures measured inside the combustion chamber and the NO_x and CO concentrations in the exhaust gas stream.

2. Experiment

2.1. Vertical combustor with internal circulation

The vertical combustor had a cylindrical shape with height 600 mm and diameter 316 mm, as shown in the diagram in Fig. 1. A fuel nozzle was located at the center of the bottom of the furnace and was surrounded by 8 air nozzles. Exhaust ports were located between the fuel nozzle and air nozzles. The fuel inlet was located 50 mm above the bottom of the furnace, and air nozzle inlets were located at the bottom. The nozzle diameters varied depending on the experimental conditions. Due to the separate injection of fuel and air, the furnace was first preheated to a temperature higher than the auto-ignition temperature of the fuel using a premixed natural gas flame. Therefore, another nozzle was located on the top of the furnace to inject premixed natural gas into the combustion chamber. The natural gas was composed of 89.95% CH_4, 6.32% C_2H_6, 2.54% C_3H_8, 1.09% C_4H_{10}, 0.01% C_5H_{12} and 0.09% N_2. The top burner was switched off once the furnace wall temperature exceeded 850 °C. The furnace wall temperatures were measured using 6 thermocouples (R type) placed along the height of the furnace and were recorded using a temperature logging system (GL450 midi logger, GRAPHTEC Corp., Yokohama, Japan). The combustion flame was observed through the window on the front wall of the furnace. Dried sludge and natural gas were also injected through the central bottom nozzle. Air was used as a carrier gas to simulate the conventional combustion, or a mixture of CO_2 and N_2 was used as a carrier gas to simulate MILD combustion. The concentrations of O_2, CO_2, CO and NO_x in the exhaust gas stream were measured with a gas analyzer (Vario Plus, MRU, Germany; Accuracy is less than 5% reading).



Location	Air nozzle (mm)	Venturi mixer (mm)	
		Body diameter	Inlet
A	6	14	27
B	8	19	36
C	10	45	90

Fig. 2. Diagram of the horizontal cyclone combustor with external circulation.

2.2. Horizontal cyclone combustor with external circulation

A diagram of the horizontal cyclone combustor with external circulation is shown in Fig. 2. The cyclone combustor was designed to provide a thorough mixing of sludge particles and air with sufficient turbulence and had a dual cylindrical shape of length 830 mm. The sludge was fed to the combustor with a screw-type feeder and fell into the combustion chamber, and air was injected into the combustion chamber in a spiral. The main combustion chamber had a diameter of 300 mm. Air was injected through the air nozzles to entrain the combustion flue gas into the furnace. The air nozzles were designed to have different diameters depending on their locations. The sizes of the air nozzles and venturi mixers are shown in Fig. 2. The temperatures inside the combustion chamber were measured by two thermocouples and recorded using the temperature logging system. When damper #1 was open and damper #2 was closed, the combustion flue gas was directly exhausted through damper #1, which simulated conventional air combustion. When damper #1 was closed and damper #2 was open, some of the combustion flue gas was re-injected through the air nozzles into the combustion chamber before being exhausted through damper #2, which simulated MILD combustion. The concentrations of O_2, CO_2, CO and NO_x in the exhaust gas were determined using the gas analyzer. The combustion flame was also observed through the window.

2.3. Dried sludge

Sewage sludge obtained from a sewage treatment plant was dried in our laboratory. The sludge was then milled and sieved through a screen. Fig. 3 is a microscopic image of the sludge at 100× magnification. As shown in the figure, the size of the sludge particle ranged from 400 to 650 μm. A screw-type feeder was used to feed in the sludge at a constant rate. The sludge was then injected into the combustion chamber by the carrier gas. A consistent sludge injection into the furnace was found in the experiments. The results obtained from the elemental analysis of the dried sludge are also summarized in Table 1.

3. Results and discussion

3.1. Determination of injection velocities

In the vertical combustor, MILD combustion was obtained with the separate injection of fuel and air after switching off the premixed natural gas burner. Combustion tests with natural gas were conducted to determine the suitable air and fuel injection velocities for stable MILD combustion in the vertical combustor. The air and natural gas injection velocities were varied by using air and fuel nozzles with different diameters. The excess air ratio ranged from 1.0 to 1.2 during the combustion tests. The stability of the combustion was evaluated with the temperatures measured inside the combustion chamber and the CO and NO_x concentrations in the exhaust gas stream. Table 2 summarizes the combustion test results. As shown in the table, stable MILD combustion was found when the fuel injection velocity (V_f) was as high as 110 m/s. The air injection velocity (V_a) demonstrated a lesser effect on the combustion stability than the fuel injection velocity. This indicated that the fuel injection velocity needed to be high enough to transport the fuel to the top of the combustion chamber so that the fuel could come into contact with the fully preheated air. The most stable combustion for natural gas was found at fuel and air velocities of 110 m/s and 16 m/s, respectively. With these experimental conditions, the temperature variation inside the combustion chamber and the exhaust gas concentrations measured during the test are presented in Figs. 4 and 5, respectively. The combustion mode was switched from conventional combustion to MILD combustion by switching off the premixed natural gas flame at the top burner. Based on the temperature and gas concentration variations, the points of time for switching to MILD mode are indicated on the figures. However, due to the response time (20–30 s) of the gas analyzer, the actual points of time for switching to MILD mode may be different from where indicated on the figures. As shown in Fig. 4, a uniform temperature distribution was found along the height of the combustion chamber during MILD combustion. While the temperature variation during conventional combustion was as much as 130 °C, it significantly decreased to less than 50 °C during MILD combustion. Due to the uniform temperature distribution, a combustion flame was rarely found inside the combustion chamber, and the NO_x concentration decreased from 80 ppm to 12 ppm after switching to MILD mode. In addition, the very slight increase in the CO concentration indicates stable, complete combustion in the MILD mode.

3.2. Computational fluid dynamics analysis

From the combustion tests using the vertical combustor with internal circulation, the most stable MILD combustion was obtained

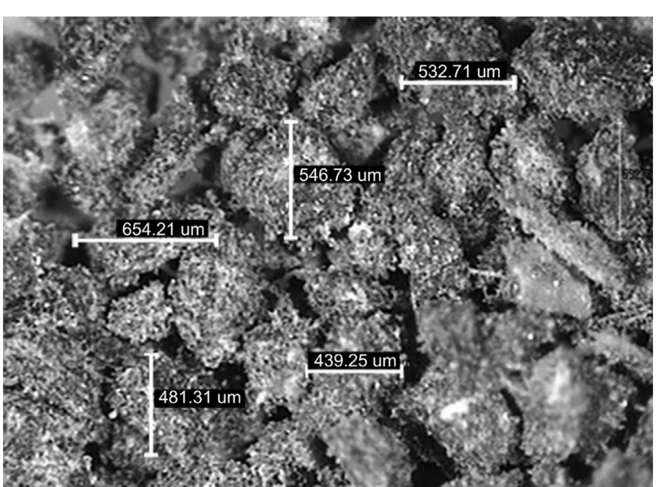


Fig. 3. Microscopic image of the sludge sample at 100× magnification.

Table 1
Elemental composition of the sludge sample.

	C (%)	H (%)	O (%)	N (%)	S (%)	LHV (kcal/kg)
Sludge	27.9	4.2	20.2	3.6	0.01	2737

Table 2
Combustion test results with variations in the fuel and air injection velocities.

No.	Fuel injection nozzle		Air injection nozzle		Combustion test result
	Nozzle diameter (mm)	Injection velocity (m/s)	Nozzle diameter (mm)	Injection velocity (m/s)	
1	1.8	86	4.2	25	>1000 ppm CO emission
2	2.0	70	2.6	66	>1000 ppm CO emission
3	2.2	90.8	5.6	14.8	Stable combustion but slightly increased CO emission
4	2.0	110	5.4	16	Stable combustion
5	2.0	110	5.0	18.6	Stable combustion

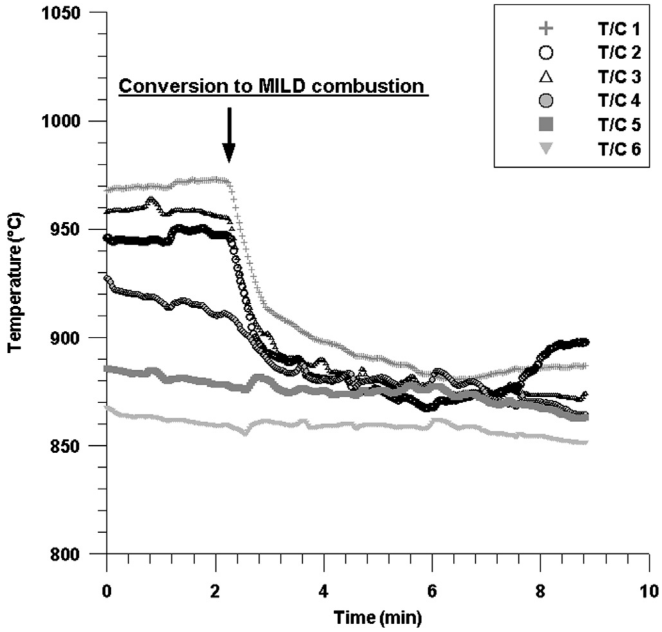


Fig. 4. Temperature variation inside the vertical combustor during the test with natural gas at $V_f = 110$ m/s and $V_a = 16$ m/s.

at $V_f = 110$ m/s and $V_a = 16$ m/s. A computational fluid dynamics (CFD) analysis was conducted to understand the flow pattern inside the vertical combustor at those conditions. SIMPLE algorithm provided by a commercial program (FLUENT 6.3, ANSYS Inc., Canonsburg, U.S.A.) was used for the CFD analysis. One-eighth of the total combustion chamber volume was considered for the CFD analysis because the same configuration is repeated in the other portions. The CFD model had the same configuration as the vertical combustor: the fuel nozzle was located 50 mm above the bottom of the combustion chamber, and the air nozzles were located at the bottom. The fuel nozzle diameter (D_f) was 2 mm, and the air nozzle diameter (D_a) was 5.6 mm. A schematic diagram of the combustor considered for the CFD analysis is shown in Fig. 6. The result

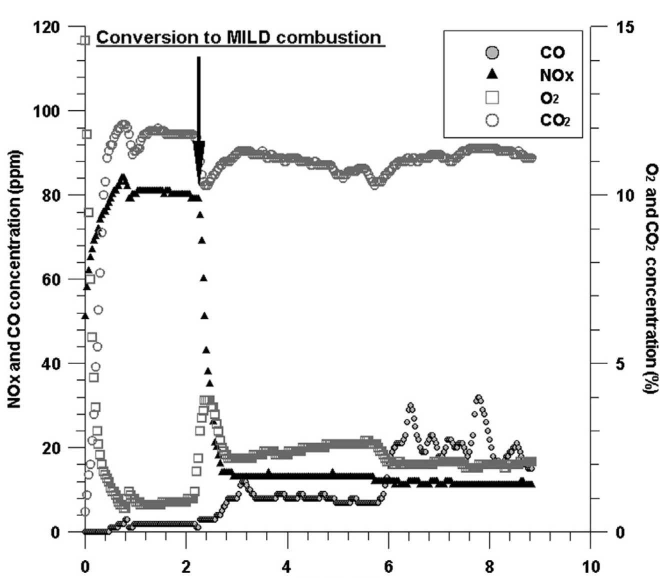


Fig. 5. Exhaust gas concentrations from the combustion of natural gas with $V_f = 110$ m/s and $V_a = 16$ m/s.

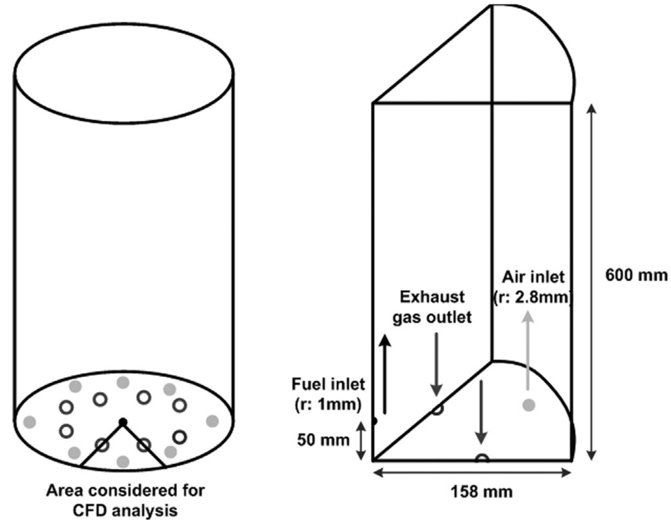


Fig. 6. Schematic diagram of the vertical combustor considered for CFD analysis.

obtained from the CFD analysis is presented in Fig. 7. As shown in the flow pattern in Fig. 7, both the fuel and the air consistently reached the top of the combustion chamber. The CFD analysis results were consistent with the combustion test results and indicated that the fuel injection velocity needed to be high enough to transport the fuel to the top of the combustion chamber. In addition, fuel and air velocities of 110 m/s and 16 m/s, respectively, were suitable to have stable MILD combustion of natural gas with the vertical combustor.

3.3. Combustion of dried sludge in vertical combustor

The suitable nozzle diameters, V_f and V_a were determined for MILD combustion of natural gas in the vertical combustor. The experimental and CFD analysis results for the combustion of natural gas showed that the fuel injection velocity was an important factor in stable MILD combustion. The results also indicated that V_f needed to be high enough to transport the fuel to the top of the combustion chamber. Because dried sludge has a different momentum than natural gas, the fuel nozzle diameter and injection

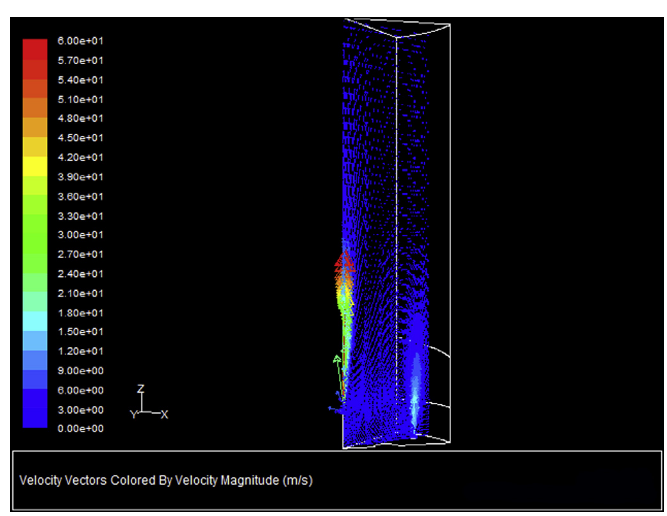


Fig. 7. Velocity magnitude (m/s) obtained from the CFD analysis for $V_f = 110$ m/s and $V_a = 16$ m/s.

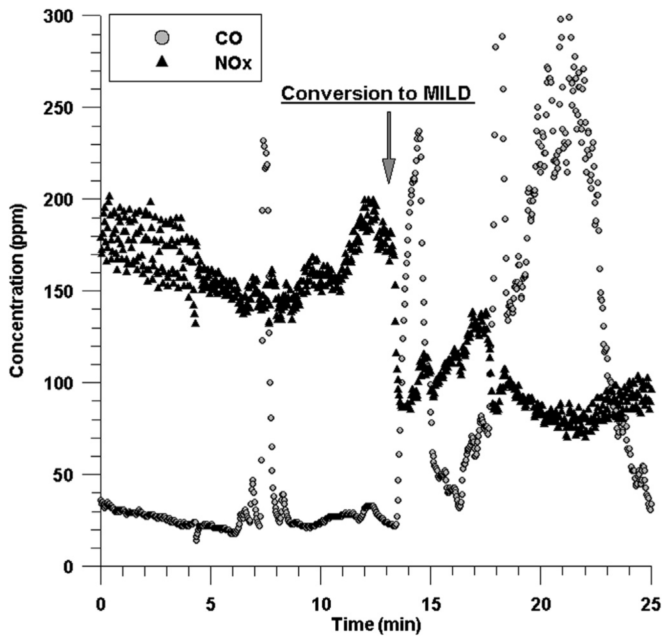


Fig. 8. NO_x and CO concentrations normalized to 12% O_2 in the exhaust gas stream obtained from the test with a natural gas flow rate of 11.5 L/min and a sludge injection rate of 1.88 kg/h.

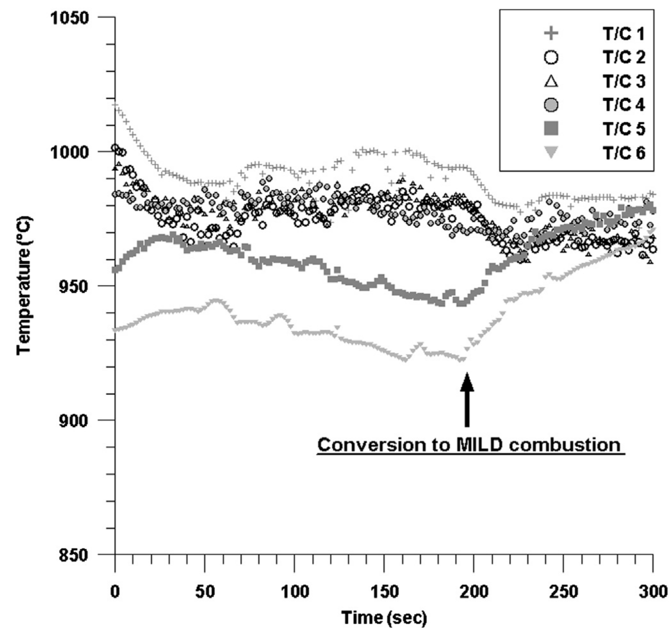


Fig. 10. Temperature variation inside the vertical combustor during the test with a natural gas flow rate of 13.5 L/min and a sludge injection rate of 1.88 kg/h.

velocity were changed for the combustion of the dried sludge. Preliminary tests were conducted with varying fuel nozzle diameters and injection velocities. As a result, the best performance was found with a D_f of 7 cm and a V_f of 31 m/s. It was also found that the dried sludge consistently reached the top of the combustion chamber.

In the beginning of the combustion process, the furnace was preheated to 850 °C using both the top and the bottom burners. The top burner was then switched off, and the dried sludge was injected through the fuel nozzle from the bottom of the combustion chamber. At first, air was used as a carrier gas to simulate conventional combustion, and then a mixture of N_2 and CO_2 replaced the air to simulate MILD combustion. The concentrations of 80% N_2 and 20% CO_2 in the mixture were chosen to simulate re-circulated combustion flue gas. Natural gas was also added to the carrier gas to have complete combustion of the dried sludge. A test was performed with a natural gas flow rate of 11.5 L/min and a sludge injection rate of 1.88 kg/h. The carrier gas (air or N_2/CO_2) was injected at a flow rate of 60 L/min to obtain the desired fuel injection velocity of 31 m/s. Air was injected through 8 nozzles surrounding the fuel nozzle, and an excess air ratio of 1.05 was maintained during combustion. Fig. 8 shows the NO_x and CO concentrations normalized to 12% O_2 in the exhaust gas stream during the test. While the NO_x concentration decreased from approximately 180 ppm to 80–100 ppm, the CO concentration increased to 300 ppm after switching to the MILD mode. In addition, the temperature variation decreased only slightly from approximately 100 °C–70 °C, as shown in Fig. 9. Thus, unstable combustion was obtained with these test conditions.

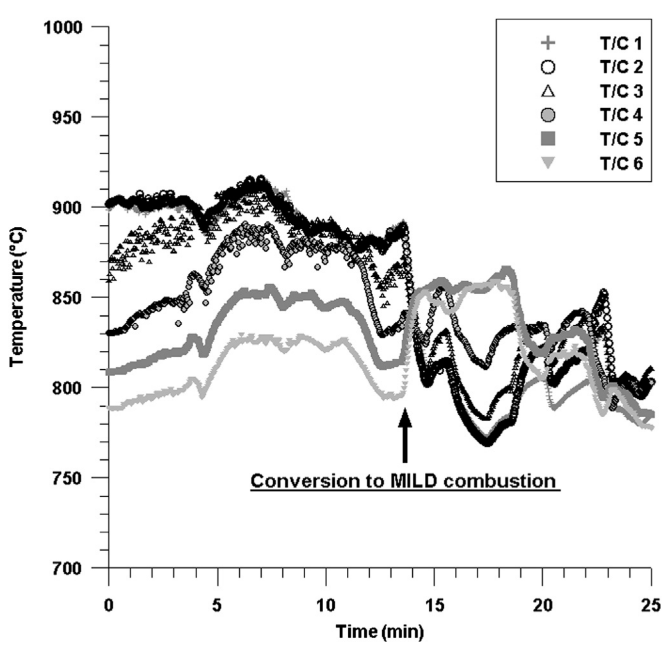


Fig. 9. Temperature variation inside the vertical combustor during the test with a natural gas flow rate of 11.5 L/min and a sludge injection rate of 1.88 kg/h.

An additional test was therefore conducted with an increased natural gas flow rate of 13.5 L/min and a sludge injection rate of 1.88 kg/h. The other conditions such as the fuel injection velocity and excess air ratio were same as the previous test. The test results are presented in Figs. 10 and 11. As shown in Fig. 10, the temperature difference decreased to less than 50 °C after switching to MILD combustion. The NO_x concentration significantly decreased, while the CO concentration slightly increased. Successful MILD combustion was therefore found with this increased natural gas flow rate. For the vertical combustor with internal circulation, the injection of the natural gas was necessary to obtain stable MILD combustion of the dried sludge. However, the performance of the vertical combustor was highly dependent on the flow pattern inside the combustion chamber. With an optimized design of the vertical combustor and operating conditions, stable MILD combustion of the dried sludge may be obtained without using natural gas.

3.4. Combustion of dried sludge in horizontal cyclone combustor

In the vertical combustor, stable MILD combustion was obtained with the co-injection of natural gas with dried sludge, and the flow pattern inside the combustion chamber was found to be an important factor. Therefore, the horizontal cyclone combustor was designed to

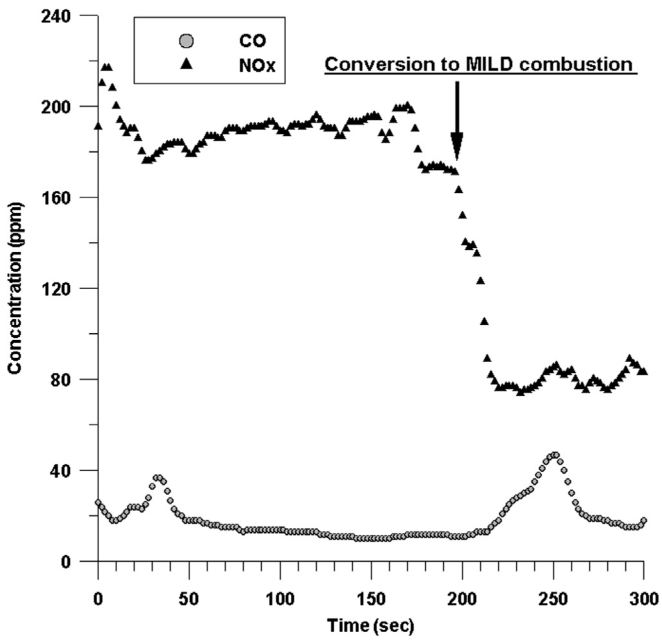


Fig. 11. NO_x and CO concentrations normalized to 12% O_2 in the exhaust gas stream obtained from the test with a natural gas flow rate of 13.5 L/min and a sludge injection rate of 1.88 kg/h.

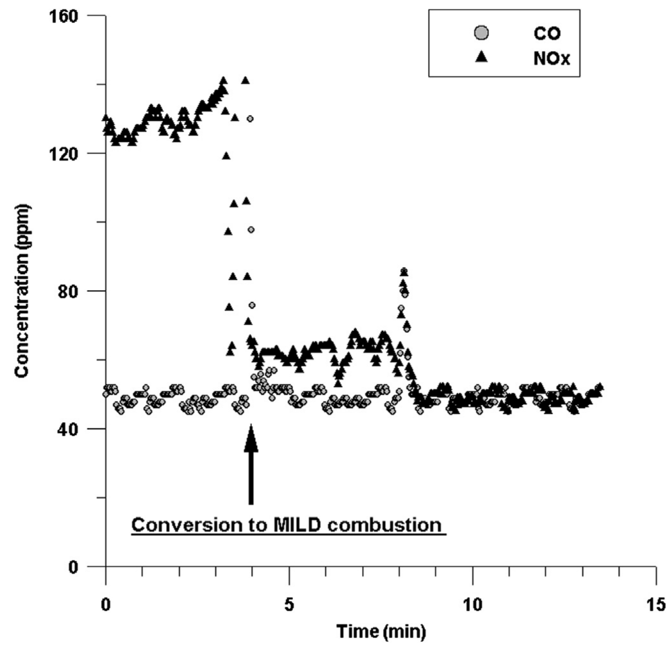


Fig. 13. NO_x and CO concentrations normalized to 12% O_2 in the exhaust gas stream during the test with a sludge feed rate of 7.6 kg/h using the horizontal cyclone combustor with external circulation.

provide a thorough mixing of sludge particles and air with sufficient turbulence. Tests were carried out in the conventional combustion mode and the MILD combustion mode using the two dampers as described in the experimental section. As a result of preliminary tests, high levels of CO emissions were found when air was injected through nozzles B and C, whose locations are shown in Fig. 2. Therefore, recirculated air was injected only through the nozzle located at A. Several preliminary tests were conducted to find the best excess air ratio for stable combustion. Because dried sludge has a lower heat value than natural gas, a higher excess air ratio was required.

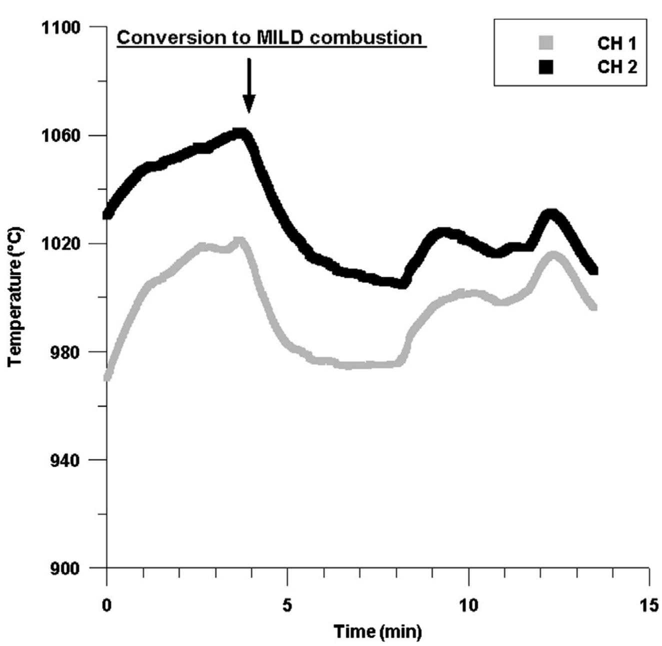


Fig. 12. Temperature variation during the test at a sludge feed rate of 7.6 kg/h using the horizontal cyclone combustor with external circulation.

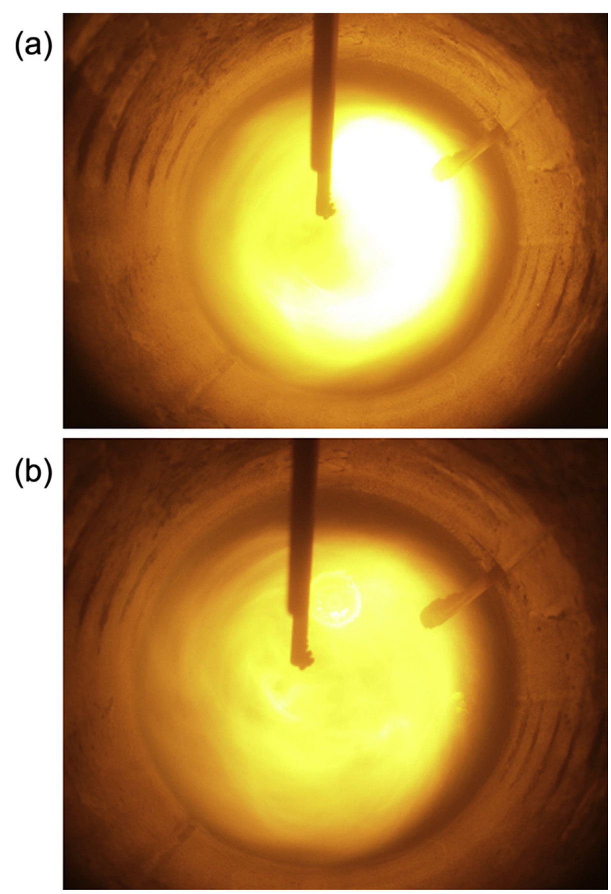


Fig. 14. Pictures of the combustion flame during (a) conventional and (b) MILD combustion using the horizontal cyclone combustor.

Figs. 12–14 show the results obtained with the optimized conditions at a sludge feed rate of 7.6 kg/h and a total air flow rate of 1200 L/min. Air was injected from 6 nozzles located at A, and the air injection velocity at each nozzle was 110 m/s. The excess air ratio with these conditions was 2.1. Figs. 12 and 13 show the temperature variation inside the combustion chamber and the NO_x and CO concentrations normalized to 12% O_2 in the exhaust gas stream, respectively. The temperature variation decreased from 40 to 60 °C to 15–25 °C after the switch to MILD mode. In addition, the NO_x concentration significantly decreased, whereas the CO concentration did not change. Fig. 14 compares the conventional combustion flame with the MILD combustion flame. While the combustion flame was clearly visible during conventional combustion, it was rarely visible during MILD combustion. This indicates that the peak temperature inside the combustion chamber during conventional combustion is much higher than the peak temperature during MILD combustion. This may contribute to the reduction in NO_x emissions after the switch to MILD mode. These results suggest successful MILD combustion of the dried sludge with the horizontal cyclone combustor.

4. Conclusions

MILD combustion was performed to reduce NO_x emissions from the combustion of dried sludge. Two different types of combustors were designed and tested for the MILD combustion. The test results with both combustors show that MILD combustion is very effective in reducing NO_x emissions from the combustion of dried sludge; however, the combustor configuration and operating conditions should be carefully determined to maintain stable MILD combustion because the combustion stability is sensitive to the flow pattern in the combustion chamber. It was relatively difficult to control the flow pattern in the vertical combustor with internal circulation. In the vertical combustor, stable MILD combustion of dried sludge was obtained with the co-injection of natural gas with the dried sludge. The horizontal cyclone combustor was designed to improve the mixing of the dried sludge with air. An external recirculation technique was applied to the horizontal combustor to better control the flow pattern inside the combustion chamber. With optimized conditions, the NO_x emissions were significantly reduced in the MILD mode while CO emissions maintained similar levels before and after the switch to MILD combustion. Further research is to be conducted on the improvement of the design of the horizontal cyclone combustor to reduce the excess air ratio during MILD combustion of the dried sludge.

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